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14. ABSTRACT
The objectives of this program are to synthesize highly nonlinear optical liquids and liquid crystals and employ them to design/ fabricate nonlinear image-transmitting fiber array faceplates that are capable of all-optical self-activated limiting agile frequency lasers in the entire visible region. In the performance period, nonlinear neat organic liquids capable of two-photon and Excited state absorption have been synthesized and characterized with various transient optical techniques. Measurements show that they possess desirable nonlinear optical such as low-freezing pint, non-volatile, transparent for low light level and possess large effective nonlinear absorption coefficients and molecular photonic energy level structures. These properties are conducive to large dynamic range optical limiting action against nanosecond laser pulses if incorporated in nonlinear fiber array device. Light-weight and compact optical limiter capable of large field of view and clamping threat laser pulses [pulsed or cw] to below the MPE-level of eye and optical sensors.

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Nonlinear liquids and liquid crystals, fiber array, optical limiter, eye and sensor protection, multiple time scale, visible to infrared, large field of view and dynamic ranges.

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1. Overview of Issues and Solutions for Agile frequency Pulsed Laser Protection.

The objectives of this program are to synthesize highly nonlinear optical liquids and liquid crystals and employ them to design/fabricate nonlinear image-transmitting fiber array faceplates that are capable of all-optical self-activated limiting agile frequency lasers in the entire visible region. The resulting devices will overcome many of the limitations confronting current devices and materials under development, and will extend the application dynamic ranges [temporal, spectral and laser power].

Direct intentional or accidental exposures to agile frequency laser radiation will cause temporary or severe permanent damages and pose the most challenging task for eye and sensor protection. Passive all-optical switchings have been investigated as viable solutions to meet these challenges. In these processes, the incident light triggers 'instantaneous' (shorter than the laser pulse duration) changes in the medium's characteristics [polarization state, absorption, electronic level populations, and other temporal- spatial characteristics] by virtue of its intensity, which in turn act on the optical field to modify/control its transmission. Examples of such all-optical or self-action processes are nonlinear absorptions, nonlinear scattering and defocusing effects. There have been intense development efforts [ref.1-9] for such self-action materials and devices. In particular, materials that possess *Reverse Saturable Absorption [RSA]*, *Two-Photon Absorption [TPA]* and *Excited State Absorption [ESA]* or *Nonlinear Scattering properties [NS]* (e.g. carbon black suspension), have been shown to be effective in some cases. To date, these materials/devices still face one or more of the following limitations in their practical implementation:

I. "Saturation Effect and Dynamic Range" - In general, RSA materials have low switching threshold ($<<\mu J$), but are (linearly) absorptive and thus their viewing and image transmission capability is limited. Since the initial photo-absorption process involves single photon transition between the molecular levels involved, RSA materials can be easily 'bleached', i.e. the absorption electronic state is depopulated by the laser. TPA materials are more desirable because they are transparent at low light level, and the initial transition is via two-photon absorption. Materials with large two-photon absorption constant are capable of limiting (of nanosecond laser pulses) threshold at the desired sub-$\mu J/cm^2$ fluence level. However, TPA materials will also suffer from population depletion at high incident laser fluence. The saturation [and limited dynamic range] problem becomes even more acute if the limiting materials are in form of solutions made by dissolving or suspending two-photon absorbers in passive solvents.

This limitation has prompted development of neat two-photon absorbing materials in our program. Furthermore, by developing neat liquids that also possess Excited State Absorption [ESA] and rapid population regeneration properties, the dynamic range can be dramatically enhanced.

II. "Temporal Limitation" - Another limitation common to these TPA, RSA, ESA and CBS materials is that the basic limiting mechanism is intensity dependent, and therefore, while they are capable of limiting nanosecond or shorter laser pulses by virtue of the higher laser intensity for a given energy, they are ineffective against jamming or damage by longer-pulsed or cw lasers. On way of circumventing this limitation is to develop TPA material [as in our proposed program] which exhibit excited states that are

long-lived, or doping the neat liquid with suitable amount of nonlinear scatterers or absorbers to facilitate optical limiting actions/mechanisms [such as thermal/density self-defocusing, bubble formation, wide-angle scattering ...etc]. Some preliminary successes were demonstrated with C60 doped ILC in the previous program

III. "Bulky Optics, Small Field of View" – In order to provide the necessary optical gain to make the nonlinear absorption/scattering processes more efficient, almost all devices developed today employ configurations with bulky focusing/collimating lens, and apertures and beam stops [see later section]. Besides being impractical and non-user friendly, such optical systems are characterized by very small field of view. In our program, we have developed compact fiber array devices that possess good viewing and image transmission characteristics [e.g. large field of view, automatic spatial frequency selectivity], and high performance sensor protection capabilities [low threshold, low clamped transmissionvalue, large dynamic range].

This program was specifically tailored to improve on various aspects of the SRI 1x goggle in which the primary protection against nanosecond laser pulses is a layer of nonlinear alcohol-based Carbon Black Suspension CBS in front of a Fiber Image Inverter as shown in Fig. 1 below:

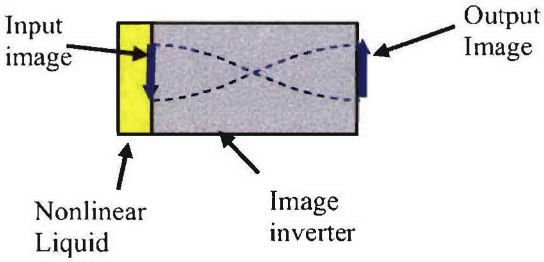

Fig. 1 Schematic of the CBS-Fiber Image Inverter assembly used for Optical Limiting action in SRI 1x goggle

Previous studies have shown that the SRI device is capable of below-MPE encircled energy limiting performance up to an incident laser fluence of ~ 1 mJ/cm^2 for nanosecond laser pulses but the device 'suffers' the following limitations:

1. The liquid for CBS is volatile and thus heavy metallic vacuum seals are needed, adding to the weight of the goggle assembly.
2. CBS does not protect the Image Inverter and can be catastrophically damaged by nanosecond laser pulses of mJ/cm^2 fluence or more.
3. The device's limited dynamic range is due to the finite/small amount of suspension that can be easily depleted by high intensity laser. Also the device cannot limit long-pulse [microsecond] or cw laser sources as the underlying limiting mechanism is very strongly intensity dependent.

2. Synopsis of the Program and Tasks

In previous program, we have developed nonlinear liquids – C60 doped ILC (isotropic liquid crystal) and L34 - that circumvented these limitations. They are not volatile and therefore do not require heavy metallic vacuum seal. These liquids possess nonlinear multi-photonic absorption, scattering, defocusing and bubble formation capabilities and have been shown to be effective optical limiting materials for nanosecond laser pulses with their. Nevertheless, they tend to freeze at near 0 °C, in comparison to the alcohol based CBS which do not freeze.

A major effort in this program is to synthesize and develop similar nonlinear absorbing liquids that freeze at much lower temperature, and possess similar nonlinear absorption properties as L34. By molecular engineering and use of nano-dopants, we also seek to improve upon the performance characteristics of L34 following the strategy as illustrated in c.f. Fig. 2. The program of study was structured to address the following integrally related topics:

(A) Development of Nonlinear Liquids;
(B) Testing and Characterization of the Nonlinear Liquids;
(C) Fiber Array configurations/devices design and modeling, fabrication and characterization and,
(D) Self-limiting and sensor protection tests.

The detailed Statement of Work for the 4-year program is given below.

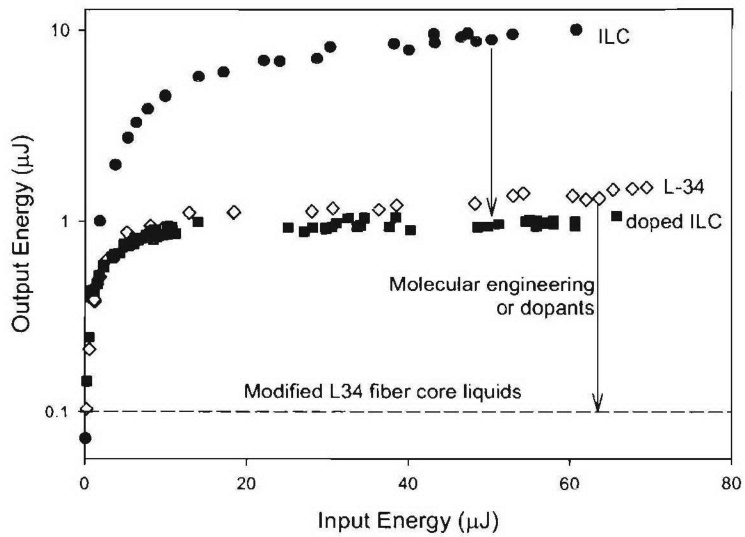

Fig.2. Lowering the clamped **transmission level** and also **freezing points** of nonlinear fiber core liquids by molecular engineering and/or use of appropriate dopants.

Task 1: Molecular Engineering and Material Synthesis

Task 1.1 Design new derivatives of nonlinear liquids – molecular engineering
Task 1.2 Synthesize new materials and perform chemical and physical evaluation
Task 1.3 Perform temperature extreme tests on liquid
Task 1.4 Deliver new liquids for testing.

Task 2: Scaled-up synthesis of nonlinear liquids and complete material/optical characterization

Task 2.1 Identify interim nonlinear liquids that withstand temperature and other extreme tests and synthesize large quantities for detailed tests and studies

Task 2.2 Characterization of linear and nonlinear optical properties of liquids

Task 2.3 Perform nonlinear transmission measurements, pump-probe dynamic spectroscopy.

Task 2.4 Analyze and design liquid mixtures to maximize nonlinear optical responses for limiting applications [e.g. Two-Photon absorption, Excited-State Absorption and Reverse Saturable Absorption].

Task 3: Optical limiting test of interim liquids with nanosecond laser pulses

Task 3.1 Optical limiting test of bulk nonlinear liquids

Task 3.2 Optical limiting test of nonlinear fiber array

Task 3.3 Optical limiting test of SRI-design (liquid layer+image inverter)

Task 3.4 Quantify, analyze performance data and correlate with material properties.

Task 4: Optimization of limiter performance and nonlinear liquid properties

Task 4.1 Employ quantitative device model developed to analyze limiting data in conjunction with measured material parameters

Task 4.2 Conduct further tests as in task 3 to further establish the quantitative roles of liquid linear and nonlinear optical properties in the limiting performance

Task 4.3 Design new liquid mixtures or employ dopants to enhance optical limiting capabilities

Task 4.4 Deliver optimized liquids for testing.

Task 5: Innovate improvement to existing device structure and configuration

Task 5.1 Increase opaqueness of fiber array or image inverter cladding by radiation bombardment, ion implantation or other molecular deposition techniques

Task 5.2 Investigate efficient means of etching image inverter

Task 5.3 Incorporate another thin nonlinear liquid layer on exit side to enhance limiter's dynamic range.

Task 6: Extending the limiting capability of device to new temporal/spectral regimes

Task 6.1 Optical limiting test with microseconds laser pulses

Task 6.2 Optical limiting and anti-laser jamming action feasibility test with cw laser

Task 6.3 Optical limiting test with 'out of band' lasers, e.g. near IR lasers.

Task 7 Deliverables

Interim and optimized nonlinear liquids will be delivered for testing and assembly at SRI or Navy Air Development Center at various stages of the program, c.f. Tasks 1.4 and 4.4.

Task 8 Reporting, program review, travel

As required by sponsoring agency.

Quarterly reports; semi-annual program review; travel to government/SRI sites.

3. Technical Accomplishments

The funding for the first year was at a reduced rate [equivalent to 75% of the proposed first year funding] and the second year effort was not funded. Nevertheless,

with partial support from other sources, the following crucial tasks have been accomplished:

Task 1.1 -1.4 Molecular Engineering and Material Synthesis

Task 2.1 – 2.4 Scaled-up synthesis of nonlinear liquids and complete material/optical characterization.

Task 3.1-3.4 Optical limiting test of interim liquids with nanosecond laser pulses

Task 4.1 -4.2 Optimization of limiter performance and nonlinear liquid properties

Task 7: Deliverables - Interim and optimized nonlinear liquids delivered for testing and assembly at SRI [and tested and characterized also at CREOL, University of Central Florida].

In the following sections, we provide more details of these accomplishments and important findings.

3.1 Materials Synthesized

For this synthesis part of the program, we collaborated with Prof. Xumu Zhang's group [at PSU] known for developing state of the art techniques [ref. 10,11] to synthesize chemically, physically and optically stable organic liquids of low melting point and large electronic nonlinearities. We have previously synthesized the liquid L34, c.f. Fig.3, using Pd-catalyzed coupling and the process involves a number of transition metal catalyzed cross-coupling reactions. The final product was purified by silica gel column and distillation [ref. 12, 13] to prevent degradation of L34 under light or oxygen.

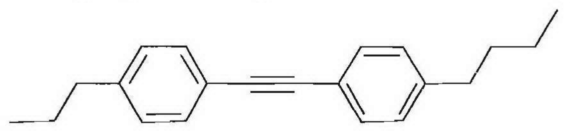

Fig. 3 Molecular structure of L34

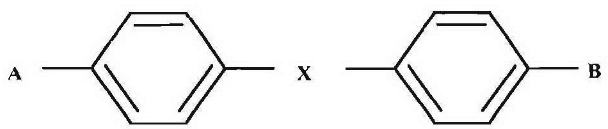

Fig. 4 General molecular structure of L34 and ILC that consists of a central core and two side groups A, B

Since the freezing points of L34 and ILC compounds are determined by the constituents groups, A, B and X, c.f. their general molecular structure as shown in Fig.4, we began our search for low-freezing point 'L34-like' liquids by synthesizing a series of compounds by varying A, B and X, i.e. we have synthesized L11, L12, L22, L23, L31...etc. In this program, we succeeded in synthesizing two <u>NEW</u> neat liquids, named CE9 and CE10, with low freezing points [~ -20 ^{0}C].

These liquids, named CE9 and CE10, have molecular structures as follow:

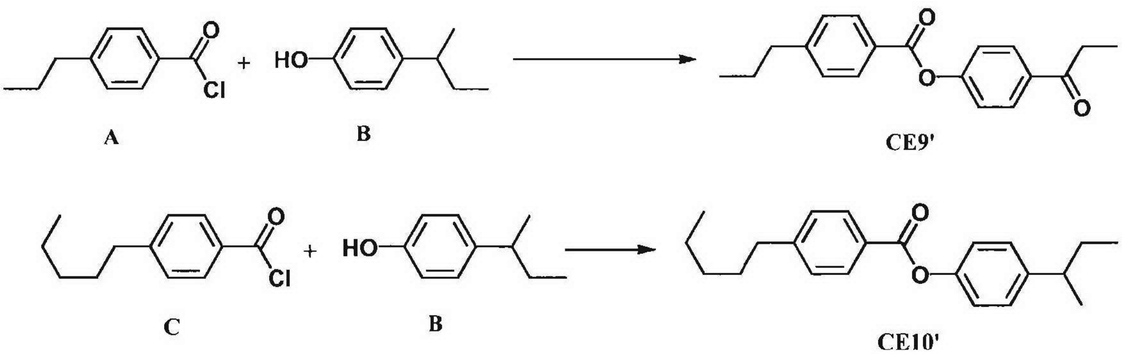

Fig. 5 Molecular structures of CE9 and CE10 which have sub-zero freezing-point.

Just as L34, CE9 and CE10 are transparent in the visible region but possess two-photon absorption characteristics, c.f. their spectra in Fig. 6 and two-photon absorption measurement data shown in Fig. 7.

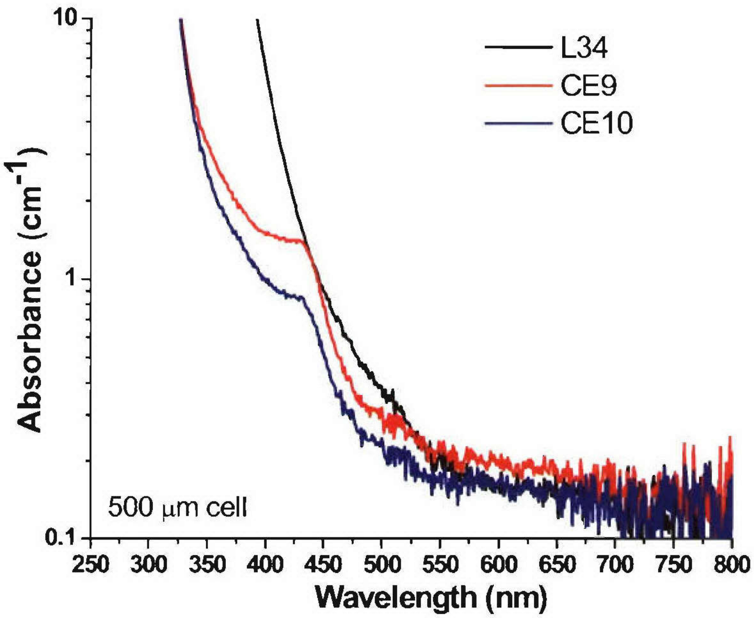

Fig.6 Molecular structures of CE9, CE10 and L34 and their linear absorption spectra

It is important to note here that the new liquids CE9 and CE10 could replace ILC [isotropic liquid crystal]- a product with unknown synthesis route - that is no longer commercially produced

3.2 Characterization

All three liquids, CE9, CE10 and L34 have recently been quantitatively characterized by femto-second, pico-second and nano-second laser pulses using time-delay pump probe, open and closed aperture z-scan techniques [ref. 14], and the nonlinear absorption/transmission characteristics of these liquids have also been investigated in these three time regimes. We summarize here some of the important findings.

Fig. 7 shows the intrinsic two-photon absorption [TPA] coefficients of L34, CE9 and CE10 measured with nanosecond z-scan techniques. In general, L34 possess higher intrinsic TPA coefficient, and a strong intensity dependent component that arises from excited state absorption [ESA] contribution. Although CE9 and CE10 possess smaller intrinsic TPA coefficients, they nevertheless also possess strong intensity dependence. As shown in detailed theoretical modeling [15], such intensity dependent [increasing] effective nonlinear absorption characteristics are crucial in ensuring a large optical limiting dynamic range.

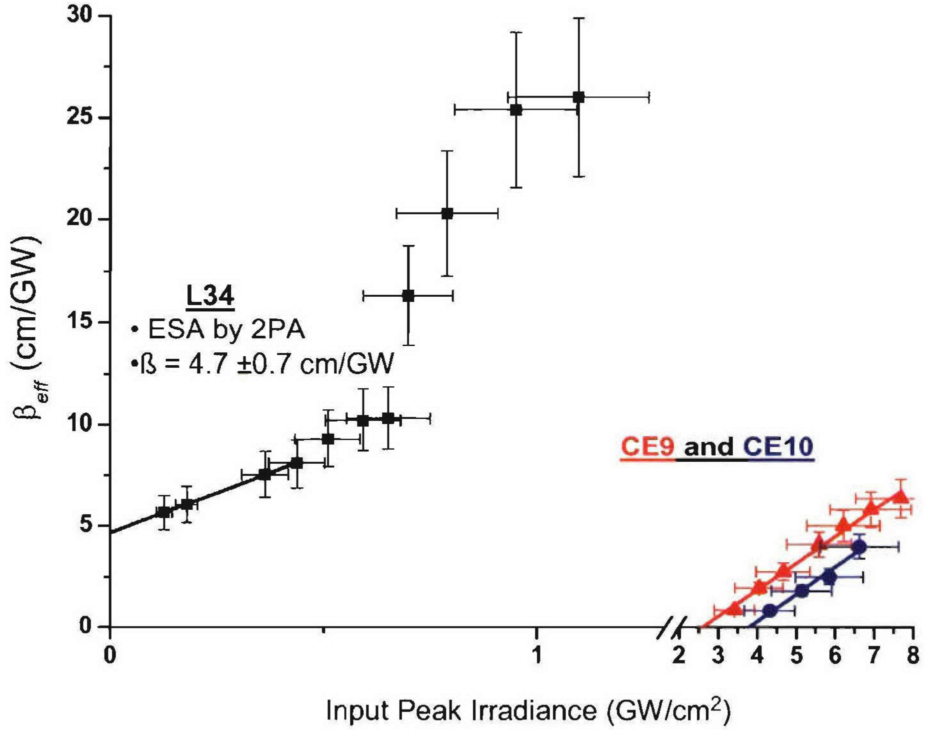

Fig.7 Nanosecond [2.49 ns] z-scan measurements for the effective two-photon absorption coefficients of L34, CE9 and CE10, showing the intrinsic values and their intensity dependent component.

Recent tests have confirmed that these liquids exhibit desirable optical limiting characteristics. Fig. 8 for example shows the limiting action of a bulk 500-μm thick L34 bulk cell for nanosecond laser pulses in an open z-scan configuration. As demonstrated in previous program, if the liquid is used as fiber guiding core, its limiting ability will be dramatically enhanced [see also section 3.4 of this report].

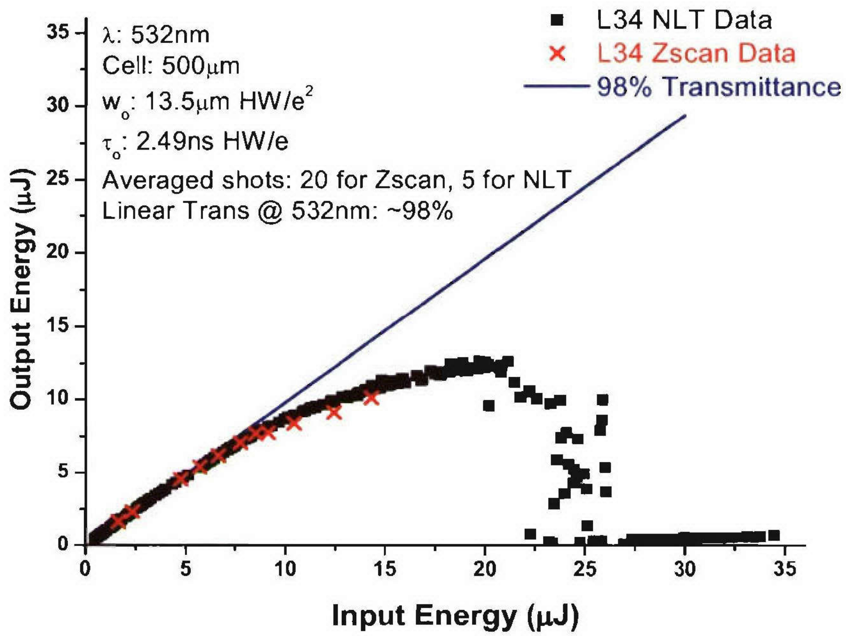

Fig.8 Nanosecond [2.49 ns] optical limiting performance of a bulk L34 liquid cell.

The newly synthesized liquids CE and CE10 exhibit similar limiting capability, c.f. Fig. 9, but at higher thresholds; these thresholds can be easily reduced with slight doping by C60 or CNT [carbon nanotubes]. Because of their organic nature, we also expect them to be suitable as host for making carbon black suspension. These low-freezing point liquids are therefore highly promising neat liquids to replace L34 and ILC in the nonlinear fiber array optical limiting device [ref. 4, 6, 15].

3.3 Molecular and Nonlinear Fiber Array Limiting Modeling

From these nonlinear absorption/transmission and other spectroscopic studies, a picture for the molecular energy level scheme of L34, CE9 and CE10 has been ascertained. As depicted in Fig. 10, there is no linear absorption from the ground state, and the first excited state is reached by two-photon absorption [TPA] with an intrinsic TPA coefficient β. In the excited state, the molecule could either absorb a photon to high-

lying excited state, or undergo intersystem crossing [from the Singlet (S) to the Triplet (T) states] and then transition to a high-lying excited state by single photon absorptions. These excited state absorption processes contribute to an intensity-dependent effective nonlinear absorption coefficient β_{eff} that can be much larger than the intrinsic value β. These combined actions of TPA+ESA result in further reduction in the transmission at high input laser intensity when the ground state population is depleted, i.e., a larger limiting dynamic range is enabled by the presence of the ESA.

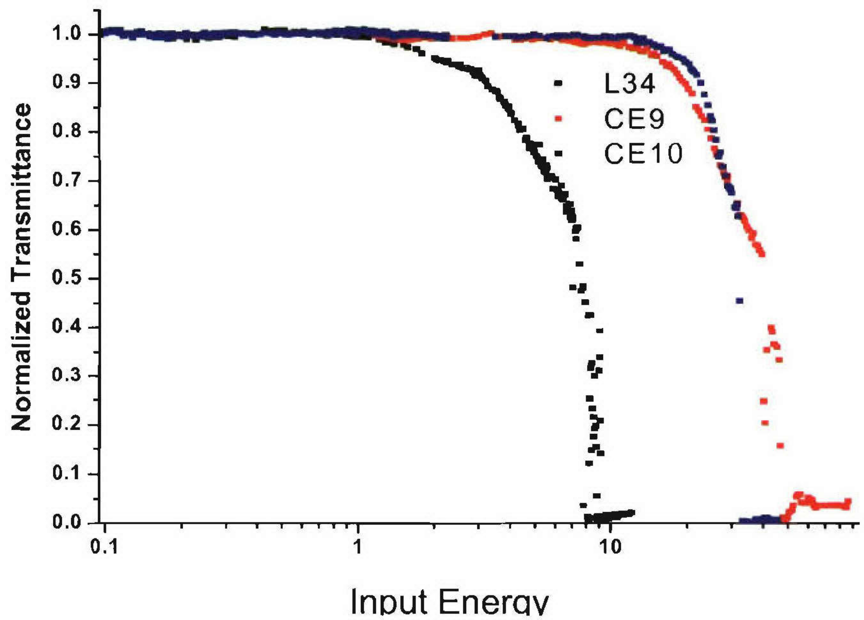

Fig.9 Output vs. input of nanosecond laser pulses [2.49 ns]through bulk L34, CE9 and CE10 liquid cells for the same z-scan geometry as used in Fig. 8.

An important point to note about neat liquid is that the entire liquid possesses the desired two-photon + *excited state absorption and population regeneration* characteristics. Neat liquids therefore will outperform solutions or suspension [with comparatively much smaller concentration of nonlinear absorber or carbon black]. This was confirmed in several experimental studies performed in previous program and also by explicit theoretical modeling, c.f. Fig. 11. Comparing the dynamic limiting ranges of a solution [with $N_T = 1.9\times10^{18}$] and neat liquid [with $N_T = 2\times10^{21}$] with about 3 orders of magnitude larger in N_T, for example, one can see that ***the optical limiting dynamic range of neat nonlinear liquid can be several [~7] orders of magnitude larger.***

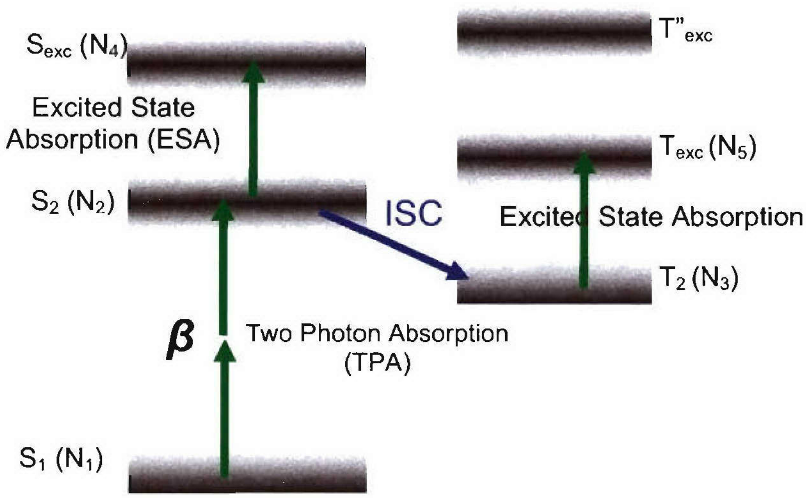

Fig.10 Molecular energy level scheme of the neat liquid L34 and its derivatives such as CE9 and CE10. The symbol N's denotes population densities of the corresponding level.

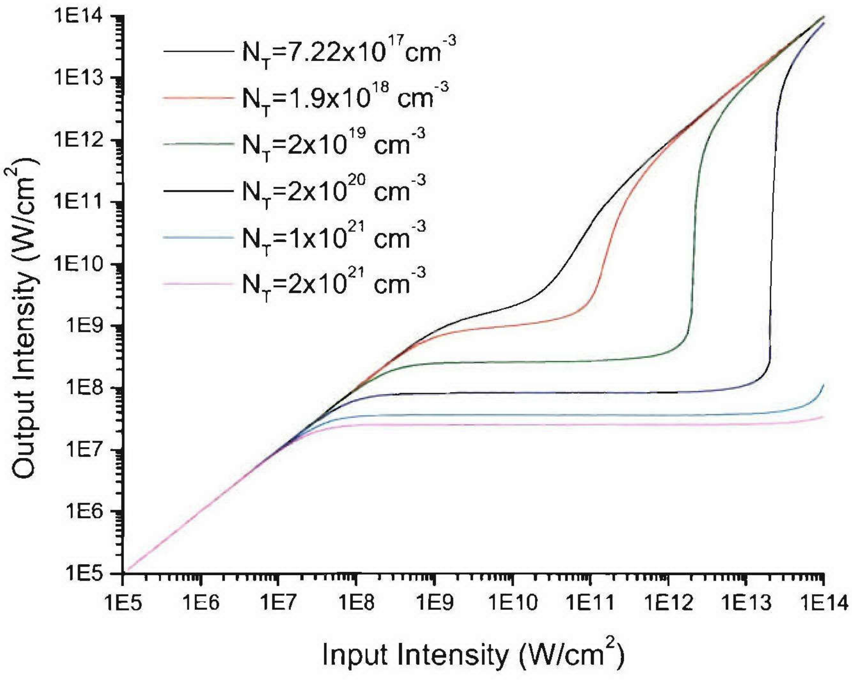

Fig. 11 Limiting performance of nonlinear fiber core liquid calculated for different molecular concentration N_T. Largest N_T corresponds to neat liquids using an intrinsic β values of 4.11 cm/GW in a fiber array [core diameter 20 μm; length 3 mm]

3.4 Liquid Crystals with very low freezing point; Non-Freezing Liquid Crystals.

To date, they [organic liquids and liquid crystals] are still among the best two-photon absorption based optical limiting materials as they posses other **unique** physical properties (e.g. capability for bubble formation, self healing). Their fluid nature enables filling into specialized structures such as photonic crystal or holey fiber, capillary arrays, and 2-, 3-D photonic crystals (opals and inverse opals) [ref. 16], Frequency Selective Surfaces [ref. 17]....etc). Besides developing neat liquids mentioned above, we have revisited the entire class of nematic liquid crystalline compounds and investigated the possibility of fabricating liquid crystal filled fiber arrays that have very wide operational temperature ranges [from ~ -40 °C to over 100 °C].

It is important to note again here that the nonlinear electronic optical responses of liquid crystals, namely, their two-photon absorption and excited state absorption properties are electronic in nature. These electronic responses [involving multi-photon transitions among the molecules' electronic states], are characterized by sub-picosecond to femtosecond electronic motion caused by the optical electric field just as in the neat organic liquid L34, CE9 and Ce10 discussed in the preceding section. Such electronic response should NOT be confused with the slower [millisecond] 'orientational' response of nematic liquid crystals used in display industry. Unlike these orientational processes, the electronic optical processes such as TPA, RSA and ESA are NOT temperature or phase sensitive, as they arise from internal electronic motion.

The worldwide explosive growth in liquid crystal display and communication industries has spawned a large and well established manufacturing/synthesis industry, resulting in nematic liquid crystals with extremely large operational temperature ranges. From these large assortments of liquid crystal mixtures, we have identified several non-freezing 'nonlinear liquids' with potentials for two-photon based optical limiting applications against nanosecond laser pulses. The following table shows three exemplary non-freezing liquid crystals and their physical/optical properties.

I. E3200-000

Clearing Point [nematic liquid crystal – isotropic]		61
Flow Viscosity at	20 °C	40
	0 °C	155
	-20 °C	1200
	-30 °C	6200
Optical anisotropy	Δn	0.1345
(20 °C, 589 nm)	n_e	1.6340
	n_o	1.4995

II. E1200-000

Clearing Point		72
Flow Viscosity at	20 °C	34
	0 °C	130
	-20 °C	870
Optical anisotropy	Δn	0.1275
(20 °C, 589nm)	n_e	1.6215
	n_o	1.4940

III. E2200-000

Clearing Point		83 °C
Flow Viscosity at	20 °C	28
	0 °C	76
	-20 °C	400
	-30 °C	1500
	-40 °C	7200
Dielectric anisotropy	$\Delta\varepsilon$	+ 8.0
(20 °C, 1kHz)	$\varepsilon_{//}$	12.3
	$\varepsilon_{\perp}$	4.3
Optical anisotropy	Δn	0.1379
(20 °C, 589 nm)	n_e	1.6357
	n_o	1.4978

3.5 Nonlinear Fiber Array Limiting Device Ongoing & Future research

One of the main thrusts in our research program is to design optical limiting devices compatible with helmet-mount goggle that are compact, light-weight and effective against agile-frequency nanosecond laser pulses. A patented optical limiting device configuration we have developed is shown in Fig. 12. The nonlinear liquids developed in this program are used to form the waveguiding cores of a fiber array. To obtain an upright image, an image inverter can be placed adjacent to the fiber array. The resolution of the inverter as well as the fiber array is dictated by the diameter of the individual fiber as each of the fiber represents an image pixel. In commercially available

fiber inverter and capillary array [for fabricating fiber array], the fiber diameter can be as small as 5 μm, corresponding to a possible resolution of ~ 100 line-pairs/mm.

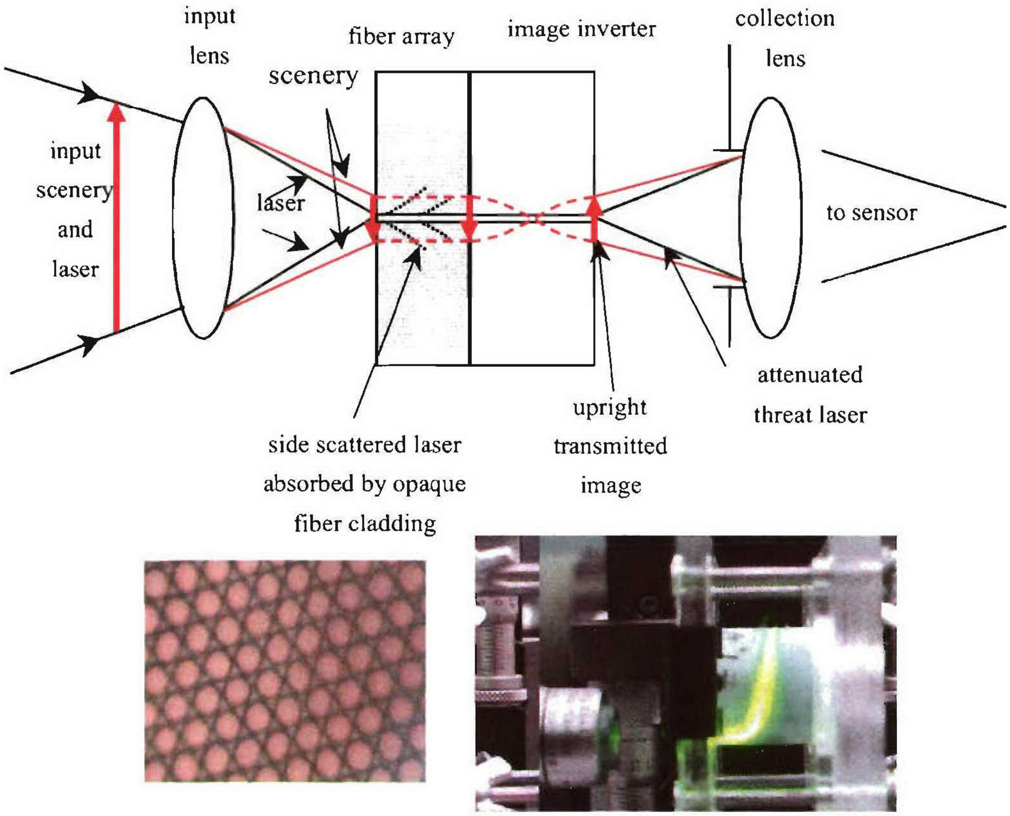

Fig.12 Nonlinear fiber array in an optical imaging system for limiting application. Lower left photo shows a cross-sectional view [in pseudo-color] of the fiber array. The pixel size [individual fiber diameter] ranges from 5 μm to over 25 μm. Lower right photo is a side view of the fiber array in tandem with an image inverter showing how an input image is inverted by the inverter.

The liquid filled fiber array is almost equivalent in weight to the layer of CBS suspension in front of the inverter, c.f. fig. 1. However, the ***fiber array geometry enables the following advantageous features compared to the bulk liquid layer used in the SRI goggle*** and other optical systems currently under development elsewhere:

I. Enhanced Nonlinear Response and Limiting action by fiber guided wave geometry

In nonlinear absorbers, e.g. TPA materials, the output intensity I_{out} is related to the input intensity I_n by $I_{out} \sim I_{in}\exp\text{-}\beta(IL)$, where (IL) is the integrated value of the laser over the interaction length L, and β is the two-photon absorption constant.

For a given incident laser power P, the IL value for a 'free-space' focusing optics in a bulk nonlinear liquid, c.f. Fig. 13, is given by:

$$(IL)_{\text{bulk}} \sim nP/\lambda \tan^{-1}(L/z_0)$$

where $z_0 = \pi n \omega_o^2/\lambda$. On the other hand, in fiber, we have

$$(IL)_{\text{fiber}} \sim PL/\pi a^2$$

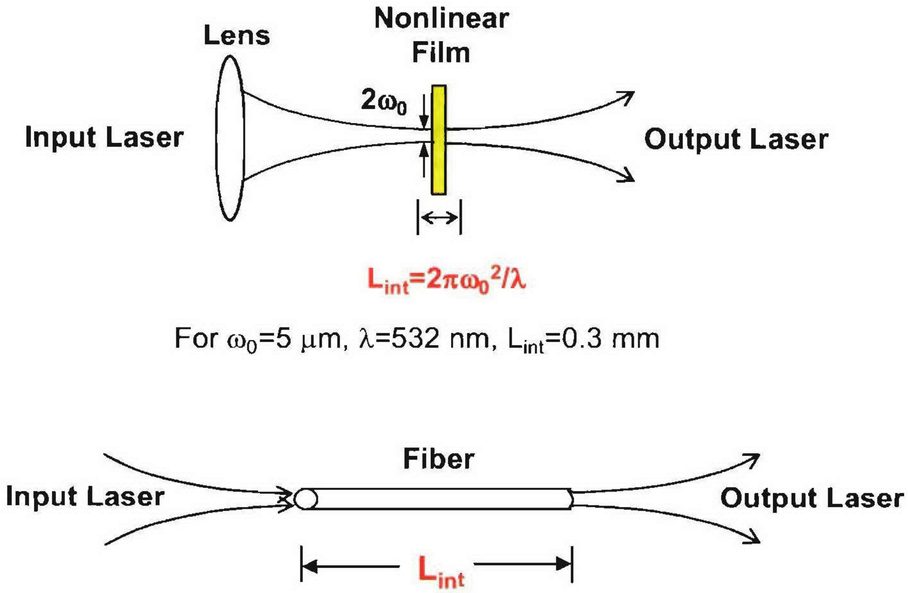

Fig. 13 Comparison of free space focusing optics and (fiber) guided geometries showing the superiority of the latter for nonlinear optical processes.

With the guided-wave propagation geometry, the fiber array will provide a much larger (IL) value. For example, if $L \sim 5$ mm, $\lambda = 0.532$ µm, $a = \omega_o \sim 15$ µm, $n=1.5$, we have $(IL)_{\text{fiber}}/(IL)_{\text{bulk}} \sim 7$, i.e. the nonlinear absorption efficiency can be enhanced by an exponential factor of 7 or more. For F1 optics used in many sensor systems, the focused beam radius $\omega_o \sim 5$ µm, and the corresponding fiber advantage factor will be much larger [> 50]. ***This translates to greatly enhanced clamping ability of the fiber array as confirmed by both quantitative numerical simulations and experiments reported previously.***

II. Compactness and compatibility with helmet mount goggle systems

In comparison with other commonly used optical set-up involving focusing and recollimating optics, c.f. Fig. 14 upper figure, the fiber array [lower figures] is extremely compact. The entire sensor protection element [sealed fiber array] is about 3 mm thick, which is 100 folds smaller than the ~30 cm space occupied by a conventional 'free-space'

dual-focal-planes optics [ref 18]. Such compact fiber array can be easily integrated with helmet mount goggles and other similar optical systems.

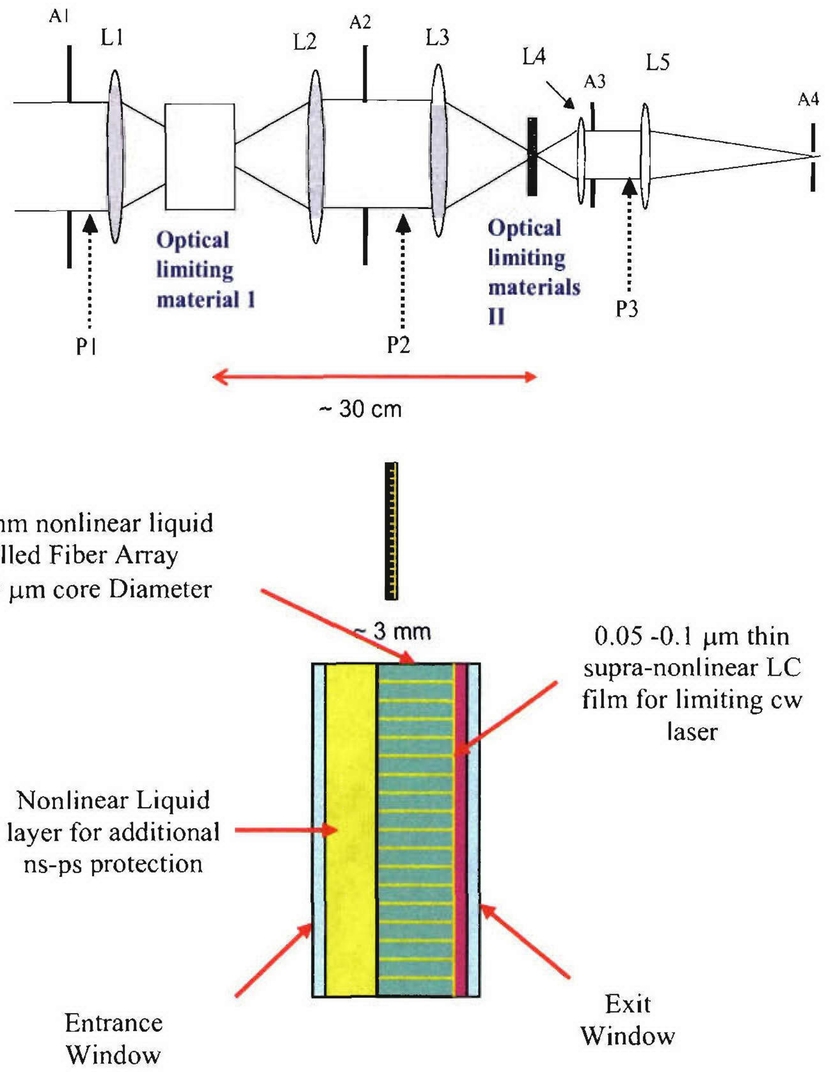

Fig. 14 Comparison of 'Free space' optical set up [*upper*] with the nonlinear fiber array [*middle*]. *Lower* figure shows a blow-up view of the nonlinear fiber array with additional protection capabilities. Overall thickness of the entire fiber array is same as the liquid layer used in the SRI goggle [see Fig. 1].

III. Multiple-time-scale and multiple-spectral region protection capability

Another advantageous feature of the nonlinear fiber array we have investigated is the feasibility of optical limiting/protection against longer laser pulses and cw intense light source. Protection against lasers [or flares, glints] can be accomplished, for example, by incorporating an extremely nonlinear liquid crystal thin film on the fiber array, as

schematically depicted in Fig. 14. The liquid crystal film will respond to the polarized light by crystalline axis rotation with a time constant ranging from microsecond to millisecond depending on the intensity of the laser [the higher the intensity, the faster is the rotation] [ref. 19]. Accordingly, such nonlinear optical film placed at the second focal plane [the exit side of the fiber array] will provide the necessary protection against long-pulsed or cw lasers [ref. 7].

Instead of the liquid crystal layer which works only with polarized light, one can employ nonlinear liquids doped with fullerenes or other RSA absorbers, nano-dopants such as carbon nanotubes, gold or silver nano-spheres/wires/rods These doped liquid will defocus or nonlinearly absorb or scatter the laser light, thereby limiting/clamping its transmission at high intensity. They could also provide effective protection against lasers [pulsed or cw] in other spectral regions [e.g. near infrared to mid-infrared 0.7 μm – 3 μm], as well as the visible regime.

In view of these promising performance characteristics of the nonlinear fiber arrays and the nonlinear liquids/liquid crystals, these projects clearly deserve further studies and development efforts, and are currently being pursued with the supports from other agencies.

4. Conclusion

Nonlinear neat organic liquids capable of TPA+ESA have been synthesized and characterized with various transient optical techniques. Measurements show that they possess several desirable properties that are conducive to large dynamic range optical limiting action against nanosecond laser pulses. If incorporated in nonlinear fiber array device, we anticipate devising light and compact optical limiting device capable of large field of view and clamping threat laser pulses to below the MPE-level of eye and optical sensors. With appropriate modifications, the nonlinear fiber arrays could also provide protection against lasers in other time scales and spectral regions.

5. Other Accomplishments

4.1. Master and Ph. D thesis

Two students working on this program have completed their graduate thesis:
(1) Mike Stinger – MS Electrical Engineering
(2) Jiangwu Ding – Ph. D. Electrical Engineering

4.2 Technology transfer

- Consultant to a Air Force Research Laboratory [WPAFB] SBIR Phase II program on liquid crystal based sensor protection and optical limiting device development awarded to BEAM Engineering Corporation, Winter Park, Florida. Project completed in 9/2005.

4.3 Invention Disclosure [Filed: 6/2006 with Intellectual Property Office]

Inventors: I. C. Khoo and Douglas H. Werner
Title: Liquid crystal containing core-shell nano-spheres for reconfigurable optical-, infrared- and Terahertz-frequency negative and zero index materials.

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